PCT

WORLD INTELLECTUAL PROPERTY ORGANIZATION
International Bureau

INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification 7 :
H04R 25/00, 1/40, 3/00

A1

(11) International Publication Number: WO 00/65873

(43) International Publication Date: 2 November 2000 (02.11.00)

(21) International Application Number: PCT/CA00/00463

(22) International Filing Date: 27 April 2000 (27.04.00)

(30) Priority Data:
60/131,471 28 April 1999 (28.04.99) US

(71) Applicant (*for all designated States except US*): GENNUM CORPORATION [CA/CA]; P.O. Box 489, Station A, Burlington, Ontario L7R 3Y3 (CA).

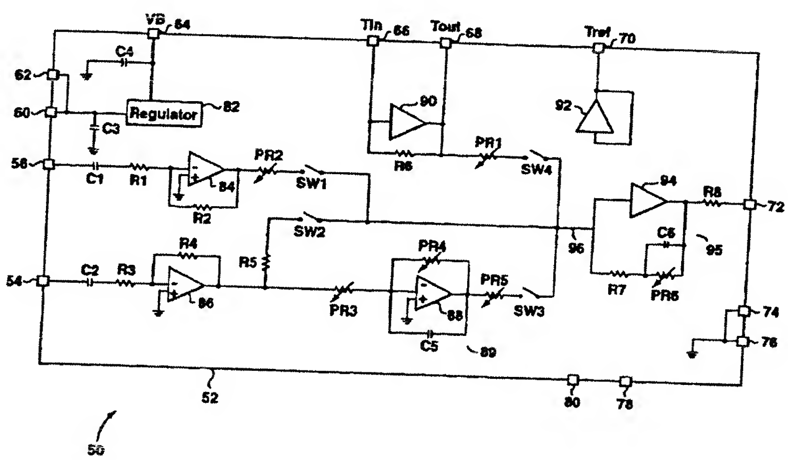
(72) Inventors; and
(75) Inventors/Applicants (*for US only*): ARMSTRONG, Steve [CA/CA]; 2171 Winchester Court, Burlington, Ontario L7P 3M7 (CA). CSERMAK, Brian [CA/CA]; 130 York Road, Dundas, Ontario L9H 1M3 (CA). MACINTOSH, Douglas, Scott [CA/CA]; 368 Otterbein Road, Kitchener, Ontario N2B 3V9 (CA). SCHMIDT, Mark, Peter [CA/CA]; 33 Woolwich Street South, Breslau, Ontario N0B 1M0 (CA).

(74) Agent: BERESKIN & PARR; 40 King Street West, 40th floor, Toronto, Ontario M5H 3Y2 (CA).

(81) Designated States: AE, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, CA, CH, CN, CR, CU, CZ, DE, DK, DM, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TR, TT, TZ, UA, UG, US, UZ, VN, YU, ZA, ZW, ARIPO patent (GH, GM, KE, LS, MW, SD, SL, SZ, TZ, UG, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GW, ML, MR, NE, SN, TD, TG).

Published
With international search report.
Before the expiration of the time limit for amending the claims and to be republished in the event of the receipt of amendments.

(54) Title: PROGRAMMABLE MULTI-MODE, MULTI-MICROPHONE SYSTEM



(57) Abstract

A multi–mode, multi–microphone system for use with a hearing aid or amplification device has two omni–directional microphones. The system includes programmable circuitry including programmable resistors and can operate in a two microphone omni–directional mode, a two microphone directional mode, a single microphone directional mode, a low frequency equalized two microphone directional mode, a telecoil input mode, and a mixed microphone input and telecoil input mode. Any number of these modes may be preprogrammed and stored by the system so that a user can select a desired mode, as required. Advantageously, the system allows the amount of equalization in the low frequency equalized two microphone directional mode and the amount of telecoil input mixing in the mixed telecoil and microphone mode to be programmably variable quantities. As a result, numerous variants of these modes are possible and may be selected as desired by a manufacturer, dispenser, or user. The microphone system is calibrated by adjusting programmable resistors so that the sensitivity of each omni–directional microphone is matched in all two microphone modes and so that a desired directional response is obtained in the two microphone directional mode for any given spacing between the omni–directional microphones.

FOR THE PURPOSES OF INFORMATION ONLY

Codes used to identify States party to the PCT on the front pages of pamphlets publishing international applications under the PCT.

AL	Albania	ES	Spain	LS	Lesotho	SI	Slovenia
AM	Armenia	FI	Finland	LT	Lithuania	SK	Slovakia
AT	Austria	FR	France	LU	Luxembourg	SN	Senegal
AU	Australia	GA	Gabon	LV	Latvia	SZ	Swaziland
AZ	Azerbaijan	GB	United Kingdom	MC	Monaco	TD	Chad
BA	Bosnia and Herzegovina	GE	Georgia	MD	Republic of Moldova	TG	Togo
BB	Barbados	GH	Ghana	MG	Madagascar	TJ	Tajikistan
BE	Belgium	GN	Guinea	MK	The former Yugoslav Republic of Macedonia	TM	Turkmenistan
BF	Burkina Faso	GR	Greece	ML	Mali	TR	Turkey
BG	Bulgaria	HU	Hungary	MN	Mongolia	TT	Trinidad and Tobago
BJ	Benin	IE	Ireland	MR	Mauritania	UA	Ukraine
BR	Brazil	IL	Israel	MW	Malawi	UG	Uganda
BY	Belarus	IS	Iceland	MX	Mexico	US	United States of America
CA	Canada	IT	Italy	NE	Niger	UZ	Uzbekistan
CF	Central African Republic	JP	Japan	NL	Netherlands	VN	Viet Nam
CG	Congo	KE	Kenya	NO	Norway	YU	Yugoslavia
CH	Switzerland	KG	Kyrgyzstan	NZ	New Zealand	ZW	Zimbabwe
CI	Côte d'Ivoire	KP	Democratic People's Republic of Korea	PL	Poland		
CM	Cameroon	KR	Republic of Korea	PT	Portugal		
CN	China	KZ	Kazakstan	RO	Romania		
CU	Cuba	LC	Saint Lucia	RU	Russian Federation		
CZ	Czech Republic	LI	Liechtenstein	SD	Sudan		
DE	Germany	LK	Sri Lanka	SE	Sweden		
DK	Denmark	LR	Liberia	SG	Singapore		
EE	Estonia						

Title: Programmable Multi-Mode, Multi-Microphone System

FIELD OF THE INVENTION

The present invention relates to the fields of hearing aids and personal amplification devices. In particular, the present invention relates to a programmable multi-microphone system for use with such devices that is capable of operating in different modes.

BACKGROUND OF THE INVENTION

A key component of any hearing aid or other personal amplification device is the microphone system which receives acoustic signals and converts them into electrical signals for processing in the hearing aid or device. A microphone has a response which is either directional, i.e. dependent on the direction of sound incidence, or omni-directional, i.e. independent of the direction of incident sound. A directional response may be advantageous for a user in noisy listening environments where the user is particularly or solely concerned with sound originating from a specific source. In such cases, the desired signal is usually a source located in front of the hearing aid wearer or user and the noise is typically competing speakers or background babble originating from the sides or rear of the speaker. Because the user requires a greater signal to noise ratio (SNR) to understand speech than a person with normal hearing capability, a directional response that attenuates sounds originating from the sides or the rear of the user is advantageous. Conversely, in quiet environments, an omni-directional microphone system is often more desirable.

An omni-directional microphone usually has a single inlet tube at which air pressure is transformed into a voltage. Directionality in a single microphone can be achieved by including inlets both in front of and behind a diaphragm in the microphone and by adding an acoustic resistor across a hole in the back inlet. It is also known to use a front and rear pair of omni-directional microphones to form a directional microphone

system. In such a multi-microphone system, the difference between the output of the front microphone and an electronically delayed version of the output of the rear microphone is typically taken. The shape of the directional response of such a system will depend on, among other parameters, the value of the electronic delay of the rear microphone signal and the distance separating the inlets of the two microphones. By varying these parameters, the response can take on different cardioidal shapes.

For example, United States Patent No. 5,757,933 to Preves et al. discloses an apparatus having first and second non-directional (or omni-directional) microphones and a switch mechanism for allowing a user to switch between a non-directional mode in which only one the first microphone output is enabled and a directional mode in which both microphone outputs are used. In the directional mode, the phase and amplitude of the inverted second microphone output can be adjusted so that the hearing aid manufacturer can vary the directionality response pattern between a cardioid pattern and a "super" or modified cardioid pattern, as desired by a hearing impaired user. Adjustments may also be made to compensate for differences in manufacturing tolerances between the first and second microphones.

However, many hearing aids are intended to exhibit a fixed directionality response and so there may be no need to adjust the cardioidal shape of the directional response of a microphone system according to a user's preferences as is done by Preves et al. Rather, what is lacking in the prior art is a system which allows a manufacturer to automatically provide a desired directional response for any given distance between omni-directional microphones. This distance may vary considerably in different devices, for example from behind-the-ear (BTE) hearing aids to in-the-ear (ITE) hearing aids. The system of Preves et al. is limited to use with an ITE hearing aid. Furthermore, the ability to adjust the phase delay and gain in the system of Preves et al. also requires manual adjustment of variable circuit components.

In addition, in a multi-microphone directional system, the

microphones should be matched in terms of both sensitivity (or gain) and phase. Similar models of component microphones may differ unacceptably with respect to sensitivity. While Preves et al. contemplate making adjustments to compensate for differences in manufacturing tolerances, no manner of automatically nor optimally doing so to provide a specific directional response is suggested. Manual adjustments are only made in response to the reaction of the hearing impaired individual user, which may be a time-consuming and laborious process.

Directional microphone systems also suffer from low frequency (bass) loss of acoustic inputs, especially when the distance between omni-directional microphones is small, such an in an ITE hearing aid. Because of this inherent acoustical filtering, the system transmits lower acoustic frequencies less strongly than higher acoustic frequencies, and a reduced signal-to-noise (SNR) ratio results. To counter this problem, low frequency emphasis or equalizations circuits have been included in directional microphone systems. However, in providing gain to the attenuated low frequency components, such an equalization circuit also boosts up the internal noise energy of the microphones in the system. For some hearing aid wearers, this often leads to objectionably high noise levels. Moreover, in prior art systems capable of operating in both a directional mode and an omni-directional mode, both modes of operation would be affected by the reduced SNR resulting from inclusion of a low frequency equalization circuit. This is problematic since low frequency loss of acoustic information is generally not a concern in omni-directional systems.

Finally, although many hearing aid microphone systems permit switching between a microphone input and a telecoil input, and although some systems also provide for a combined or mixed microphone and telecoil input, prior art systems do not allow a user to adjust the extent of input mixing according to possible listening preferences in different sound environments.

SUMMARY OF THE INVENTION

In one aspect the present invention provides a microphone system comprising: (a) a first omni-directional microphone for receiving an acoustic signal and providing a first electrical signal in response; (b) a second omni-directional microphone for receiving said acoustic signal and providing a second electrical signal in response, said first and second microphones being located near a surface of a housing for said microphone system and being separated by a certain distance on said housing; (c) programmable circuitry coupled to said first and second microphones for providing a delayed version of said second electrical signal and for matching the sensitivity of said first microphone with the sensitivity of said second microphone; and (d) switching means coupled to said programmable circuitry for optionally providing one of at least a first mode signal and a second mode signal at a node, said first mode signal comprising a sum of said first electrical signal and said second electrical signal, and said second node signal comprising a sum of said first electrical signal and said delayed version of said second electrical signal.

Preferably, the microphone system further comprises (e) a programmable low frequency equalization circuit having an input connected to said input node and an output for providing an output signal having a programmably variable amount of low frequency equalization. Also preferably, said equalization circuit provides said output signal with no low frequency equalization when said first mode signal is provided at said node and said equalization circuit provides said output signal with a desired amount of low frequency equalization when said second mode signal is provided at said node.

In one embodiment, the programmable circuitry includes (a) a first programmable resistor coupled between said first omni-directional microphone and said node; (b) a series combination of a delay stage and a second programmable resistor, said series combination being coupled between said second omni-directional microphone and said node, said delay stage including a third programmable resistor; (c) a fixed resistor

coupled between said second omni-directional microphone and said node. In another aspect, the present invention provides a method of calibrating this embodiment of the microphone system comprising the steps of: (a) adjusting said first programmable resistor such that the sensitivity of said first microphone matches the sensitivity of said second microphone when said first mode signal is provided at said node; (b) adjusting said second programmable resistor such that the sensitivity of said first microphone matches the sensitivity of said second microphone when said second mode signal is provided at said node; (c) adjusting said third programmable resistor such that, when said second mode signal is provided at said node, said second mode signal provides a desired directional response with respect to said acoustic signal for any value of said distance between said first and second omni-directional microphones.

Further objects and advantages of the invention will appear from the following description, taken together with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

In the drawings which illustrate, by way of example, preferred embodiments of the invention:

Figure 1 shows a prior art directional microphone system that uses two omni-directional microphones;

Figure 2 illustrates the cardioid shape of a directional response of a microphone system;

Figure 3 shows a first embodiment of the multi-microphone system according to the present invention;

Figure 4 shows another embodiment of the multi-microphone system according to the present invention;

Figure 5 shows the calibration set-up for the multi-microphone system of the present invention; and

Figures 6-8 illustrate various stages in the calibration process for the multi-microphone system.

DETAILED DESCRIPTION OF THE INVENTION

An omni-directional microphone has a response which is independent of the direction of incident sound. Figure 1 shows a known microphone system 10 which uses two omni-directional microphones 12 and 14 to obtain an overall directional response in which sounds originating from the sides 36 or the rear 38 of the system 10 are attenuated in comparison with sounds incident from the front 40 of the system 10. The signals 36, 38, and 40 are components of the overall acoustic signal received by the system 10. Referring to Figure 1, each of the omni-directional microphones 12 and 14 has an inlet tube 16 and 18, respectively, at which air pressure is transformed into an electrical signal 22 and 24, respectively. The inlet tubes 16 and 18 are located in ports in a surface or faceplate 20 of a housing (not shown) of the system 10. The inlet tubes 16 and 18, and therefore effectively the microphones 12 and 14, are separated by a distance d. In the system of Figure 1, the microphone 14 may be referred to as the front microphone and the microphone 12 may be referred to as the rear microphone.

In known manner, an electronic delay circuit 26 receives the signal 22 and outputs a delayed signal 28 whose difference with the signal 24 is obtained at 30 to provide a microphone system output signal 32. The output signal 32 exhibits a directional response with respect to the acoustic input received at 16 and 18. The signal 32 is subsequently provided to a amplification device 32, such as a hearing aid signal processing unit, which may be located in a common housing with the microphone system 10.

The directional response, in polar coordinates, of the signal 32 as a function of the angle of incidence Θ in the horizontal plane as measured from the axis of directionality 42 at the front of the system 10 (as shown in Figure 1) is generally given by

$$D(\Theta) = kd(\beta + \cos\Theta)$$

where d is the distance between the microphones 12 and 14, k is a constant,

and β is the ratio of the electronic delay in block 26 to the external delay between the microphones. The external delay between microphones 12 and 14 is effectively the distance d divided by the speed of sound in air (344 m/s). Therefore, the directional response D is a function of both the internal electronic delay in block 26 and the distance d separating the microphones 12 and 14. (In practice the directional response D will also depend on the frequency of the acoustic signal components as well as on the angle of incidence of those components in the vertical plane.)

The shape of the directional response is generally cardioidal or "heart-shaped". In the case of $\beta = 1$, the external delay equals the internal electronic delay, and the response is a pure cardioid as shown in Figure 2. Different directional responses can be obtained by lowering the value of β, so that the internal electronic delay is less than external delay. Generally, as β is lowered the directional response becomes a super cardioid in which sounds originating from the sides are further attenuated and sounds originating from the rear receive less attenuation compared to the cardioid response in Figure 2. This effect continues until a hyper-cardioid response is reached at $\beta = 0.33$. Further decreases result in a bi-directional (or "figure-8 like") response that is relatively equally sensitive to sounds arriving from the front and back, and insensitive to sounds arriving from the sides. On the other hand, increasing β distorts the cardioid shape of the response and eventually results in an omni-directional response. For most directional hearing aid applications, β would normally be varied from between 0.33 to 1.0.

Typically, a particular microphone layout (including a fixed microphone separation d) is selected along with an appropriate internal electronic delay to obtain the desired β or directional response. Therefore, in many prior art systems, both the separation d and the electronic delay have to be fixed beforehand in order to provide the desired response. The present invention provides a microphone system that allows a desired directional response to be obtained for any range of microphone separation distances, so that the microphone system can be used, for example, with

housings for both ITE hearing aids and BTE hearing aids.

Figure 3 shows a first embodiment of a microphone system 50 according to the present invention. As shown in Figure 3, the microphone system 50 may be conveniently formed monolithically as an integrated circuit 52 with pins 54, 56, 58, 60, 62, 64, 66, 68, 70, 72, 74, 76, 78, and 80.

Referring to Figure 3, the electrical signal from a first or front omni-directional microphone is supplied to pin 56, and the electrical signal from a second or rear omni-directional microphone is supplied to pin 54. The signals at pins 54 and 56 may be the signals 22 and 24 respectively in Figure 1. The microphone electrical signals are preferably buffered at 84 and 86 respectively to isolate the effect of switching between different modes in subsequent stages. The buffers 84 and 86 act to invert the microphone signals and may also provide pre-amplification to the signals. A power supply signal VB is supplied to the integrated circuit 52 at pin 64, while a regulating voltage is provided at pins 60 and 62 to an on-chip regulator 82 to protect to the microphone components from power supply fluctuations. Pins 74 and 76 are grounded, as shown in Figure 3, to provide a reference voltage to the system 50 in known manner.

A telecoil option is also provided for at pins 66, 68, and 70. A telecoil (not shown) is an external component which facilitates hearing by an impaired listener with a hearing aid on a telephone or in a looped area by suppressing the interference of background noise. A looped area basically includes a wire or cable installed in the form of a loop around the perimeter of the area. The cable is connected to an amplifier and to one or more sound sources. As an electrical current moves through the wire an electromagnetic field is created inside the loop and this is picked up by the telecoil.

As shown in Figure 3, a telecoil input Tin at pin 66 is amplified at stage 90. The output of the amplifier 90 Tout is provided to pin 68 for applications which require an external telecoil switching option. A reference voltage Tref for the telecoil component is also provided at pin 70 by stage 92.

Referring still to Figure 3, the buffered rear microphone signal is switchably fed via a resistor R5 and a programmable switch SW2 along a first path to a node 96. The buffered rear microphone signal is also switchably fed via programmable resistor PR3, a delay stage 89, programmable resistor PR5, and programmable switch SW3 along a second path to node 96. As shown in Figure 3, the delay stage 89 may comprise an amplifier 88 having, as feedback, a programmable resistor PR4 in parallel with a capacitance C5. The delay stage also provides the necessary inversion for obtaining a directional response, i.e. the difference between the front microphone signal and the delayed rear microphone signal. The telecoil output signal Tout (which is the amplified Tin signal) is also switchably fed via a programmable resistor PR1 and a programmable switch SW4 to the node 96.

All signals which are present at summing node 96 are added together to provide an input for low frequency equalization circuit 95. As shown in Figure 3, equalization circuit 95 may include an amplifier 94 with a feedback consisting of a resistor R7 in series with the parallel combination of a capacitor C6 and a programmable resistor PR6. The output of the microphone system 50 is provided at pin 72, and this signal may be fed to subsequent signal processing circuitry (not shown) in the hearing aid or amplification device. Equalization stage 95 may optionally also provide amplification of the signal at node 96.

As explained below, the programmable microphone system 50 of the present invention conveniently offers a hearing aid wearer or amplification device user with a number of possible different operational modes. Furthermore, according to the present invention, the programmable system 50 in conjunction with calibration software running on a computer with a sound card and speaker overcomes several drawbacks found in prior art systems.

By programmably and automatically adjusting the programmable resistor PR4 with the calibration software, the system 50 can provide a very wide variety of directional responses for virtually any

microphone port spacing. This gives a manufacturer the flexibility to implement the multi-microphone system 50 in different shell types and sizes – be it for BTE hearing aids, ITE hearing aids, or devices of other sizes – and thereby dramatically increases the manufacturer's fit rate. As a result, a manufacturer can automatically provide an optimum directional response for any given distance between omni-directional microphones. The specifically chosen directional response may be pre-selected by a manufacturer or it may be adjusted during a "fitting" process for a particular individual.

The omni-directional microphones must also be matched with respect to both sensitivity (gain) and phase for a directional microphone system to be effective. In most cases, microphones designed for hearing aid applications are sufficiently phase matched to not pose a concern. (Also, any mismatch in terms of the phase of the omni-directional microphone pairs may also be compensated for during adjustment of PR4 in the phase delay circuit 89.) On the other hand, microphones from different production batches may vary in sensitivity substantially, often by as much as ± 3 dB. The degree of attenuation achieved near the nulls of a directional response is adversely affected when the sensitivities of the microphones are not matched. While some microphone manufacturers offer the option of purchasing matched microphone pairs, a premium is charged for this service. In addition, even a matched pair of microphones purchased from a manufacturer may only be matched to within a certain range (for example, 1 dB) of one another, which often may still be significant enough to affect the directional response.

The microphone system 50 includes programmable resistors PR3 and PR5 in the phase delayed path of the rear microphone signal (from pin 54) and a programmable resistor PR2 in the path of the forward microphone signal (from pin 56). The programmable resistors, under control of the calibration software, allow for gain trimming of the rear microphone output signals to compensate for any mismatch between

microphone sensitivities. While two programmable resistor PR3 and PR5 are included in the rear delay path in the illustrated embodiment of Figure 3, it would also be possible to use a single programmable resistor in this path. However, the embodiment of Figure 3 is preferable since it allows better sensitivity matching, for example less than 0.1 dB, to be obtained. Such accurate matching would be difficult to achieve with only a single programmable resistor in the delay path. In addition, the inclusion of programmable gain resistor PR2 in the forward microphone path is required, as will be explained below, for sensitivity matching in a two microphone omni-directional mode of operation.

Thus, the multi-microphone system 50 of the present invention allows a hearing aid manufacturer to use an unmatched pair of microphones, eliminating the premium cost associated with purchasing matched pairs and providing generally better matching than that provide by a manufacturer. Moreover, in the event one microphone fails, only the faulty microphone need be replaced, as the programmable gain resistors (PR2, PR3, and PR5) can be readjusted with the calibration software to compensate for any mismatches in sensitivity between the new and the original microphones.

As mentioned previously, due to the inherent low-cut acoustical filtering, a directional microphone system transmits lower acoustic frequencies less strongly than higher acoustic frequencies, and a reduced signal-to-noise (SNR) ratio results. This low frequency or bass loss is accented when the distance between omni-directional microphones is small, such as in an ITE hearing aid. Low frequency emphasis or equalizations circuits used to counter this problem provide gain to the attenuated low frequency components but, at the same time, also increase the internal noise energy in the microphones. In many instances, this leads to objectionably high noise levels for the user of the hearing aid or amplification device.

The present invention minimizes this problem, by making the degree of equalization in stage 95 variable. As illustrated in Figure 3,

this may be accomplished by adjusting programmable resistor PR6. Thus, a trade-off between compensating for low frequency acoustic information loss and having a noise level that is still acceptable to a user can be made. In this manner, a manufacturer or dispenser can add an amount of low frequency boost at a suitable expense of amplifying the internal noise level in the microphones. Alternatively, the system 50 may be preprogrammed, as explained below, to provide different amounts of equalization in different modes. For example, a directional mode with a significant amount of low frequency equalization and a directional mode with only a small amount of equalization could each be separately preprogrammed in the system, allowing a user or wearer to choose between these options as desired. In addition, for modes providing an omnidirectional response to an acoustic input, the equalization circuit 95 can be programmably configured to provide no low frequency equalization (i.e. no boost to low frequencies) since low frequency loss is not a concern in such modes. As can be seen in Figure 3, stage 95 can be programmed to provide no equalization by reducing the resistance across PR6 to zero, effectively shorting it.

In many instances a user of a hearing aid may also wish to switch between a microphone input and an available telecoil input or to mix a telecoil input with the microphone input. The microphone system of the present invention further allows the strength of the telecoil input being mixed with a microphone input to be varied according to different preferences by means of programmable resistor PR1. Once again, such programming choices can be made by a manufacturer or dispenser during a calibration or fitting process as well as by a user of a system in which at least two modes have been preprogrammed with different amounts of telecoil input mixing.

As a result, the present invention provides a multi-microphone system which is capable of operating in several different modes. Preferably, the system 50 provides a user with at least a two microphone directional mode and a two microphone omni-directional

mode. In the two microphone directional mode, the programmable switches SW1 and SW3 are closed and the programmable switch SW2 is open. In the two microphone omni-directional mode the programmable switches SW1 and SW2 are closed and the programmable switch SW3 is open. In this mode, sensitivity matching between the front and rear microphones is achieved by programmably adjusting PR2 with the calibration software (no adjustment in the rear path takes place since R5 is a fixed resistor) so that the signals from each microphone arriving at node 96 are correlated. Because these signals are correlated, their sum results in a signal level of 6 db, twice the original signal level in each microphone. However, the internal noise energy in each microphone is not correlated, and therefore the summed signal at node 96 results in an increase in noise level of only 3 dB ($\sqrt{2}$ times the internal noise energy in each microphone). As a result, the two microphone omni-directional mode with sensitivity matching achieves a 3 dB increase in SNR. If desired, in this mode, the overall output can be attenuated by 6 dB, by adjusting the programmable resistor PR2 (with a suitably chosen value for fixed resistor R5) so that the effective result is a decrease in 3 dB in the level of the microphone noise energy relative to a single omni-directional microphone.

In addition, the microphone system 50 may also be programmably configured to provide numerous other possible operational modes. The system can provide a single microphone omni-directional mode in which only the front microphone signal (at pin 56), by closing SW1 and opening SW2 and SW3, or the rear microphone signal (at pin 54), by closing SW2 and opening SW1 and SW3, is provided to node 96. These two modes may be useful, for example, if either the front or the rear microphone fails, or if battery power is low (and hence can be conserved by operating in a lower power mode where only the operating microphone is powered). In one embodiment of the invention, one of these modes may be entered into automatically if a controller or processor in a digital hearing aid or amplification device determines that a microphone failure

has occurred or that the device's battery power is running low.

By adding selective amounts of low frequency equalization in stage 95 in the two microphone directional mode, the system 50 further provide numerous variant modes of directional operation. The equalization provided will be determined by programmable resistor PR6, as described above. Recall that there is generally no need to add equalization in an omni-directional mode, but, as previously indicated, the stage 95 may be used in an omni-directional mode to provide gain.

The multi-microphone system 50 also provides a basic telecoil mode, by closing SW4 and opening SW1, SW2, and SW3. In any of the above described non-telecoil modes, the telecoil input may also be mixed in with the inputs from the front and/or rear microphones (pins 56 and/or 54), by closing SW4 in addition to the other required switch settings for the mode. Finally, by adding only selectively attenuated amounts of the telecoil input, numerous other variant of each mixed microphone/telecoil mode are possible. The attenuation of the telecoil input is determined by the programmable resistor PR1. Note that if no mixing of the telecoil input is to occur, switch SW4 remains open in that mode.

The settings of each of the programmable resistors and programmable switches of the system 50 for any of the modes identified above may be stored in a non-volatile memory that is accessible by the microphone system 50. This non-volatile memory may be a specific memory dedicated to the system 50, or it may be a part of a larger memory used by the hearing aid or amplification device.

In Figure 3, pin 78 provides a memory or mode select which is connected to an external switch (not shown) for selecting between different ones of these preprogrammed modes of multi-microphone system 50 operation. The external switch may comprise a push button, toggle, or other type of switch positioned for easy accessibility by a user of the hearing aid or device (for example, on the housing thereof). The switch allows a user to quickly switch between the preprogrammed modes of operation. In each mode, the settings for the programmable resistors

and programmable switches of microphone system 50 are fixed and stored in a memory. The system may include any number of preprogrammed modes, and in a preferred embodiment, the system 50 includes sufficient memory for the programmable settings of at least four different operational modes to be stored. Also preferably, at least the two microphone directional mode and the two microphone omni-directional mode are among the modes preprogrammed to memory, with additional preprogrammed modes chosen by a manufacturer, dispenser, or user.

In an alternative embodiment, the telecoil input and telecoil mixing modes may be controlled by a separate switch, to facilitate mixing of the telecoil input in any of the preprogrammed microphone modes.

As well in Figure 3, the pin 80 provides a serial digital communication interface for communication between the microphone system 50 (i.e. chip 52) and a programmable micro-processor (not shown). The processor typically controls operation of the entire hearing aid or amplification device system and is housed within such a system. The micro-processor sends via pin 80 serial digital information that adjusts the programmable resistors and programmable switches of microphone system 50 according to a particular preprogrammed operational mode or as required during the calibration/ fitting steps of the microphone system 50 (described below).

It should be noted that the programmable switches SW1, SW3, and SW4 in the system 50 can be conveniently implemented by respectively using programmable resistors PR2, PR5, and PR1 which include an open circuit (infinite resistance) setting, such as the programmable resistors in the ER102 integrated circuit produced by Etymotic Research.

It will also be clear to those skilled in the art that, in delay stage 89, a fixed resistor may be used in place of PR4 and a programmably adjustable capacitor may be used in place of C5 without affecting operation of the system 50 in Figure 3. A similar change could also be made with respect to PR6 and C6 in the equalization stage 95 in Figure 3.

Figure 4 shows another embodiment of the multi-microphone system 50 of the present invention with two enhancements to the embodiment of Figure 3. First, the delay stage 89′ in Figure 4 has been modified as shown with two additional fixed resistors R9 and R10. In addition, the programmable resistor PR4 has been eliminated, with the setting of programmable resistor PR3 now controlling the amount of delay in stage 89′. The delay stage 89′ effectively provides an all pass response, unlike the delay stage 89 in Figure 3 which provides a low pass response. Otherwise, the delay stages 89 and 89′ operate similarly. Also, because the delay stage 89′ in Figure 4 does not provide an inversion of the delayed rear microphone signal, the inverting buffer in the forward microphone path (84 in Figure 3) is also not required in the embodiment of Figure 4. The inverting buffer 86 provides the necessary inversion in the delay path for the rear microphone signal in Figure 4. Non-inverting buffers (not shown) could also be included in the front and rear microphone paths; however, these are not necessary.

Furthermore in Figure 4, the programmable resistor PR2 has a fixed resistor Rs in series and a fixed resistor Rp in parallel therewith. This series-parallel combination provides higher precision during gain trimming steps when adjusting PR2. This is alternative is particularly suitable where a large portion of the available range of PR2 would not otherwise be exploited during gain trimming.

As already mentioned, the programmable multi-microphone system is initially calibrated to automatically trim out any sensitivity mismatches between the front and rear microphones (for all two microphone operational modes) and to automatically set the time (or phase) delay of stage 89 so that a desired directional response is obtained for any microphone port spacing. The calibration set-up is shown in Figure 5 for a multi-microphone system 50 with front omni-directional microphone 102 and rear omnidirectional microphone 104.

As shown in Figure 5, the calibration set-up includes a computer 110 having calibration software, according to the present

invention running thereon. The computer 110 includes a sound card 112, a speaker 114, and an A/D converter card 116. As is well understood by those skilled in the art, the sound card 112 enables the computer 110 to output sound through the speaker 114 board. Also, as indicated in Figure 5, the speaker 114 may be positioned at two different positions relative to the hearing aid (or equivalently, the hearing aid may be positioned at two different positions relative to a fixed speaker position). In a first position shown at 114-1, the speaker is positioned so that the acoustic signal emanating from the speaker reaches each microphone 102 and 104 at the same time with equal intensity. In a second position shown at 114-2, the speaker is positioned so that the acoustic signal emanating from the speaker reaches the rear microphone 104 before reaching the front microphone 102. The output of the microphone system, from pin 72, is connected to the computer via A/D converter card 116 to provide a digital version of the microphone output signal in known manner.

It is alternatively possible to calibrate the microphone system 50 after it has been integrated with a hearing aid or amplification device. In this case, the computer 110 may have a microphone (not shown) attached to it positioned to measure the acoustic output of the hearing aid or amplification device during the calibration process (instead of the computer measuring the electrical microphone system output signal).

The calibration process for calibrating the multi-microphone system of the present invention is generally divided into three main stages, as illustrated in Figure 6, 7, and 8. Figure 6 shows the first stage in which sensitivity matching for the two microphone omni-directional mode may be achieved by carrying out steps 150-164. Referring to Figure 6, this stage requires that the calibration set-up be as shown at 114-1 in Figure 5 so that the microphones 102 and 104 receive an output from the speaker 114 at the same time and with equal intensity. The programmable switches SW3 and SW4 remain open throughout this stage. With SW2 closed and SW1 open, a test sound is generated by the computer and the resultant microphone system output is measured. This measurement is first

performed on the rear microphone 104 since, in this mode, the fixed resistor R5 is in the rear microphone signal path. Next, the measurement is repeated for the front microphone 102, i.e. with SW1 closed and SW2 open. The setting of PR2 is adjusted until the measured level for the front microphone 102 most closely matches the measured level for the rear microphone 104.

Figure 7 shows a second calibration stage in which the appropriate phase delay in delay stage 89 (Figure 3) is set by carrying out steps 180-204. In step 180, the set-up is arranged so that the rear microphone 104 receives the acoustic output from speaker 114 prior to the front microphone 102, for example in the set-up 114-2 in Figure 5. In steps 182-190, the effective spacing between the front and rear microphones is measured. This is accomplished by switching SW1 and SW2 on and off in a complementary manner (with SW3 and SW4 open), so that the microphone output signal includes components of the signal received by each microphone. The phase difference of these components is calculated, converted to a time value, and subsequently to an effective microphone spacing distance value (d). From the value of d and the desired directional response, i.e. β, a target time delay for the delay stage 89 is computed (step 192). Next, with SW1 and SW4 open, a similar complementary switching action is effected on SW2 and SW3 to again obtain in step 200 a phase difference between the rear microphone direct path and the rear microphone delayed path. This phase difference is converted to the effective time delay in stage 89. The setting of PR4 (in the embodiment of Figure 3) is then adjusted until the effective time delay most closely equals the target time delay.

The third calibration stage shown in steps 210-224 in Figure 8 achieves a sensitivity match in the two microphone directional mode. The steps of Figure 8 are similar to the calibration steps of Figure 6, except in Figure 8 the output level is first measured for the front microphone 102 (with SW1 closed and SW3 open) and subsequently for the rear microphone (with SW3 closed and SW1 open). Also in the calibration

stage of Figure 8, both programmable resistors PR3 and PR5 are adjusted until the measured rear microphone level most closely matches the measured front microphone level.

In each of the calibration stages, the programmable resistors may be adjusted in any suitable manner as will be understood by those skilled in the art, such as in a heap sort, merge sort, or quick sort manner.

Once the calibration steps of Figures 6-8 have been completed, the settings for PR2, PR3, PR4, and PR5 remain the same for all modes of operation, except where the programmable resistors also operate as the programmable switches – in this case, the programmable resistors are also set to an open circuit (infinite resistance) setting when the switch is set to open. As indicated above, the settings of PR1 and PR6 may change for different operational modes.

While preferred embodiments of the invention have been described, these are illustrative and not restrictive, and the present invention is intended to be defined by the appended claims.

WE CLAIM:

1. A microphone system comprising:

(a) a first omni-directional microphone for receiving an acoustic signal and providing a first electrical signal in response;

(b) a second omni-directional microphone for receiving said acoustic signal and providing a second electrical signal in response, said first and second microphones being located near a surface of a housing for said microphone system and being separated by a certain distance on said housing;

(c) programmable circuitry coupled to said first and second microphones for providing a delayed version of said second electrical signal and for matching the sensitivity of said first microphone with the sensitivity of said second microphone; and

(d) switching means coupled to said programmable circuitry for optionally providing one of at least a first mode signal and a second mode signal at a node, said first mode signal comprising a sum of said first electrical signal and said second electrical signal, and said second node signal comprising a sum of said first electrical signal and said delayed version of said second electrical signal.

2. A microphone system according to claim 1 further comprising:

(e) a programmable low frequency equalization circuit having an input connected to said input node and an output for providing an output signal having a programmably variable amount of low frequency

equalization.

3. A microphone system according to claim 2 wherein said equalization circuit provides said output signal with no low frequency equalization when said first mode signal is provided at said node and said equalization circuit provides said output signal with a desired amount of low frequency equalization when said second mode signal is provided at said node.

4. A microphone system according to claim 1 wherein said second mode signal provides a desired directional characteristic with respect to said acoustic signal.

5. A microphone system according to claim 1 wherein said switching means optionally provides one of at least said first mode signal, said second mode signal, a third mode signal, and a fourth mode signal at said node, said third mode signal comprising said first electrical signal and said fourth node signal comprising said second electrical signal.

6. A microphone system according to claim 5 further comprising a telecoil input for receiving a telecoil input signal and wherein said switching means optionally provides one of at least said first mode signal, said second mode signal, said third mode signal, said fourth mode signal, and a fifth mode signal at said node, said fifth mode signal comprising said telecoil input signal.

7. A microphone system according to claim 6 wherein said programmable circuitry further includes circuitry for providing a variably attenuated version of said telecoil input signal.

8. A microphone system according to claim 7 wherein said switching means optionally provides one of at least said first mode signal,

said second mode signal, said third mode signal, said fourth mode signal, said fifth mode signal, a sixth mode signal, a seventh mode signal, an eighth mode signal, and a ninth mode signal at said node, said sixth mode signal comprising a sum of said first mode signal and said variably attenuated version of said telecoil input signal, said seventh mode signal comprising a sum of said second mode signal and said variably attenuated version of said telecoil input signal, said eighth mode signal comprising a sum of said third mode signal and said variably attenuated version of said telecoil input signal, and said ninth mode signal comprising a sum of said fourth mode signal and said variably attenuated version of said telecoil input signal.

9. A microphone system according to claim 1 further comprising a telecoil input for receiving a telecoil input signal and wherein said switching means optionally provides one of at least said first mode signal, said second mode signal, and a third mode signal at said node, said third mode signal comprising said telecoil input signal.

10. A microphone system according to claim 9 wherein said programmable circuitry further includes circuitry for providing a variably attenuated version of said telecoil input signal.

11. A microphone system according to claim 10 wherein said switching means optionally provides one of at least said first mode signal, said second mode signal, said third mode signal, a fourth mode signal, and a fifth mode signal at said node, said fourth mode signal comprising a sum of said first mode signal and said variably attenuated version of said telecoil input signal, and said fifth mode signal comprising a sum of said second mode signal and said variably attenuated version of said telecoil input signal.

12. A microphone system according to claim 1 wherein said programmable circuitry includes

(a) a first programmable resistor coupled between said first omni-directional microphone and said node;

(b) a series combination of a delay stage and a second programmable resistor, said series combination being coupled between said second omni-directional microphone and said node, said delay stage including a third programmable resistor;

(c) a fixed resistor coupled between said second omni-directional microphone and said node.

13. A microphone system according to claim 12 wherein said series combination further includes a fourth programmable resistor in series with said second programmable resistor and said delay stage.

14. A microphone system according to claim 1 further comprising means for communicating with a programmable micro-processor.

15. A microphone system according to claim 1 for use in conjunction with a hearing aid device.

16. A method of calibrating a microphone system according to claim 12 comprising the steps of:

(a) adjusting said first programmable resistor such that the sensitivity of said first microphone matches the sensitivity of said second microphone when said first mode signal is provided at said node;

(b) adjusting said second programmable resistor such that the sensitivity of said first microphone matches the

sensitivity of said second microphone when said second mode signal is provided at said node;

(c) adjusting said third programmable resistor such that, when said second mode signal is provided at said node, said second mode signal provides a desired directional response with respect to said acoustic signal for any value of said distance between said first and second omni-directional microphones.

17. A method of calibrating a microphone system according to claim 13 comprising the steps of:

(a) adjusting said first programmable resistor such that the sensitivity of said first microphone matches the sensitivity of said second microphone when said first mode signal is provided at said node;

(b) adjusting said second and said fourth programmable resistors such that the sensitivity of said first microphone matches the sensitivity of said second microphone when said second mode signal is provided at said node;

(c) adjusting said third programmable resistor such that, when said second mode signal is provided at said node, said second mode signal provides a desired directional response with respect to said acoustic signal for any value of said distance between said first and second omni-directional microphones.

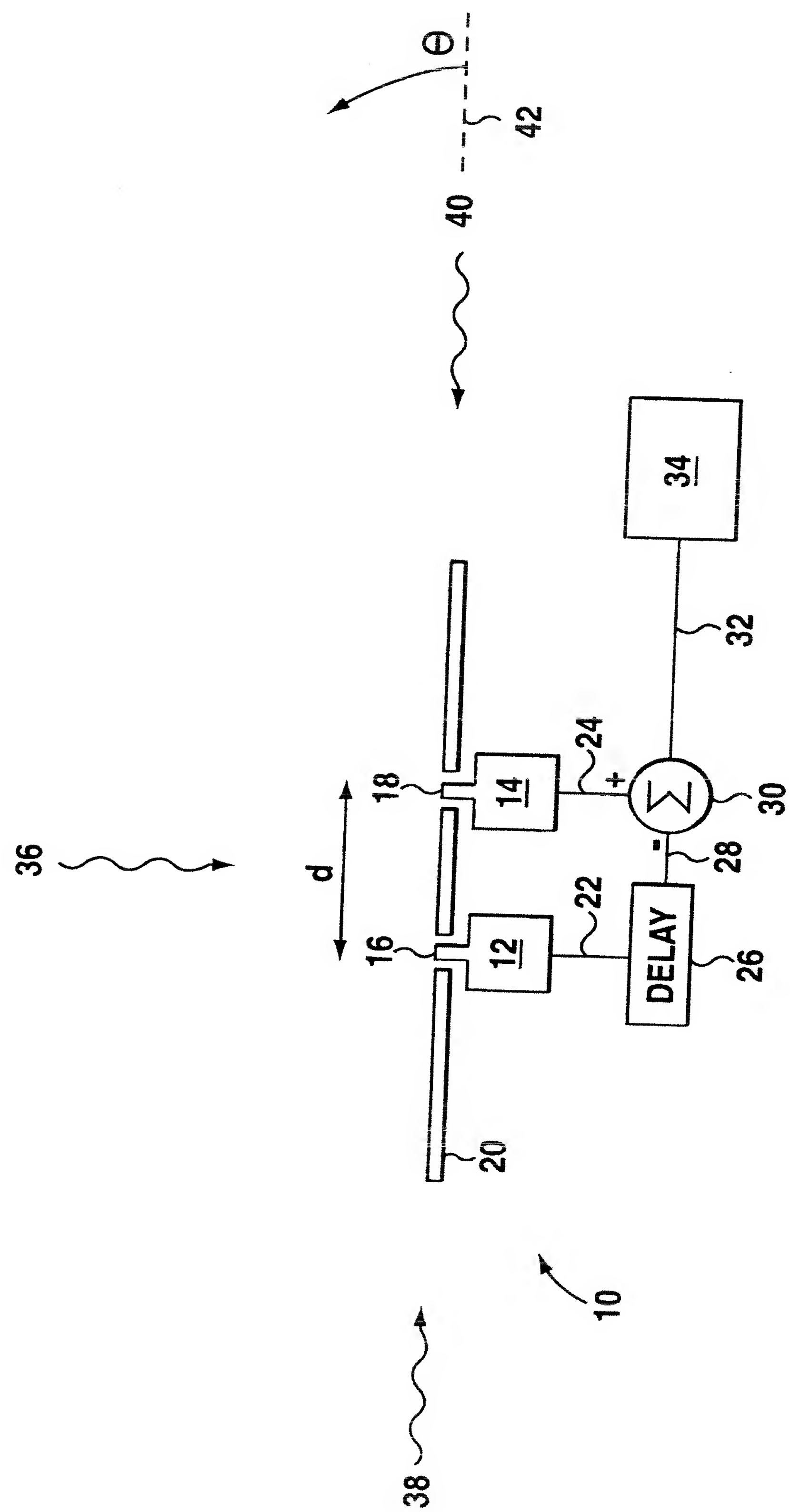


FIG. 1 (Prior art)

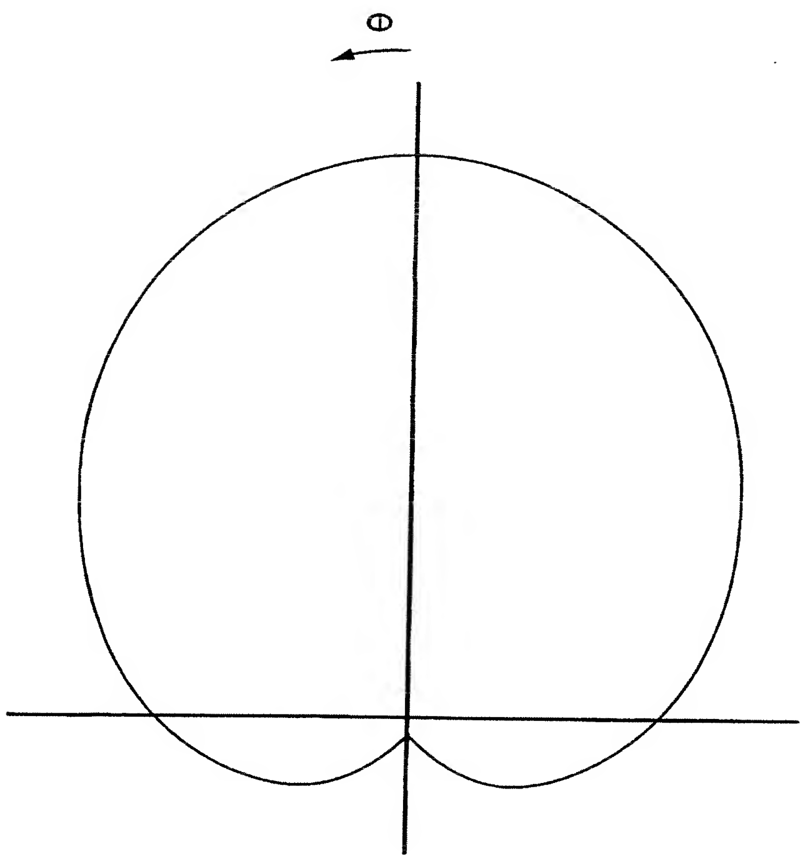


FIG. 2

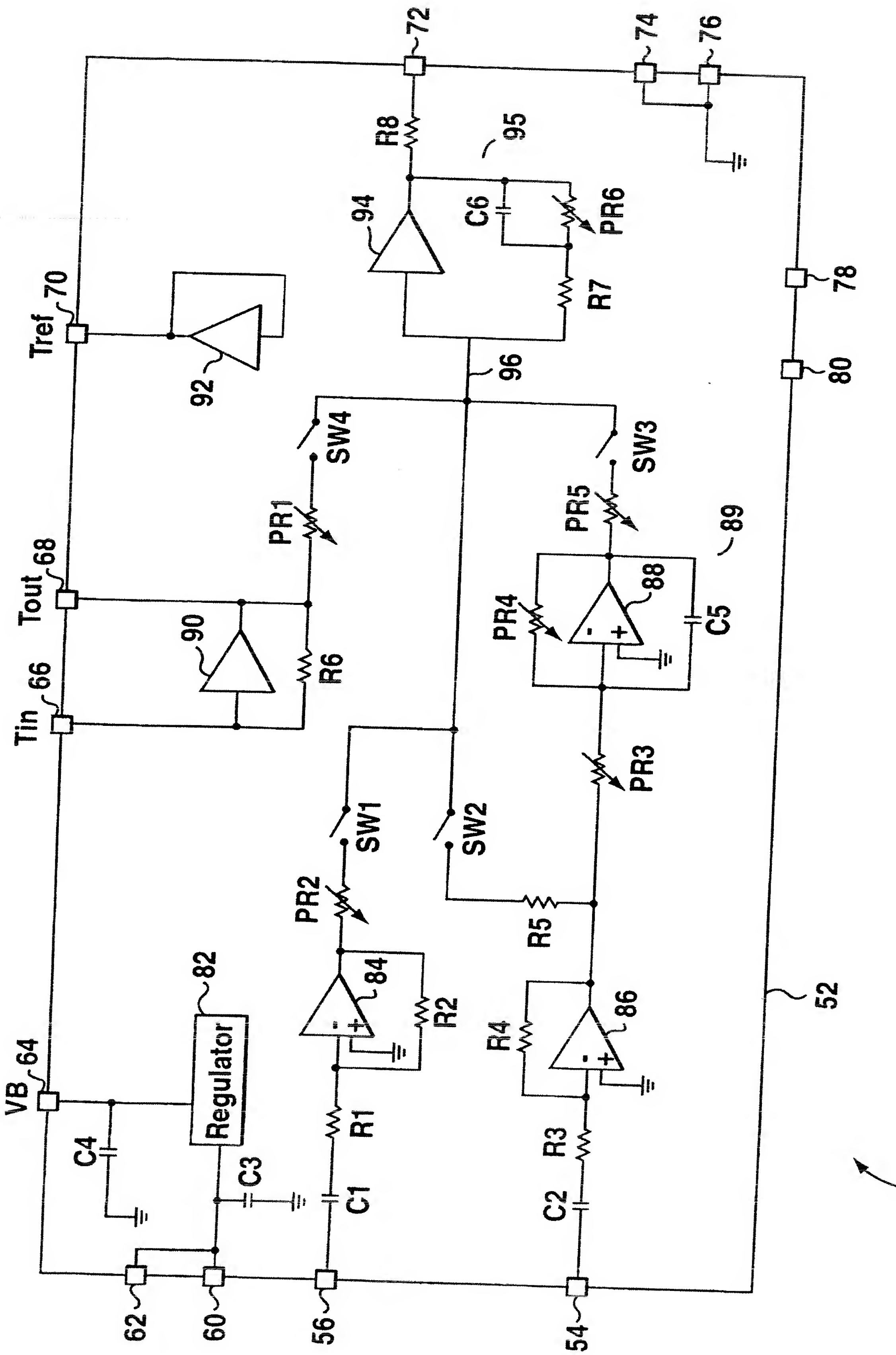

Tref
70
Tout
68
Tin
66
VB
64
72
74
76
78
80
R8
95
94
C6
PR6
R7
96
92
SW4
SW3
PR1
PR5
89
90
88
PR4
C5
R6
PR3
SW1
SW2
PR2
R5
82
Regulator
84
R2
R4
86
C4
C3
R1
C1
R3
C2
52
50
62
60
56
54

FIG. 3

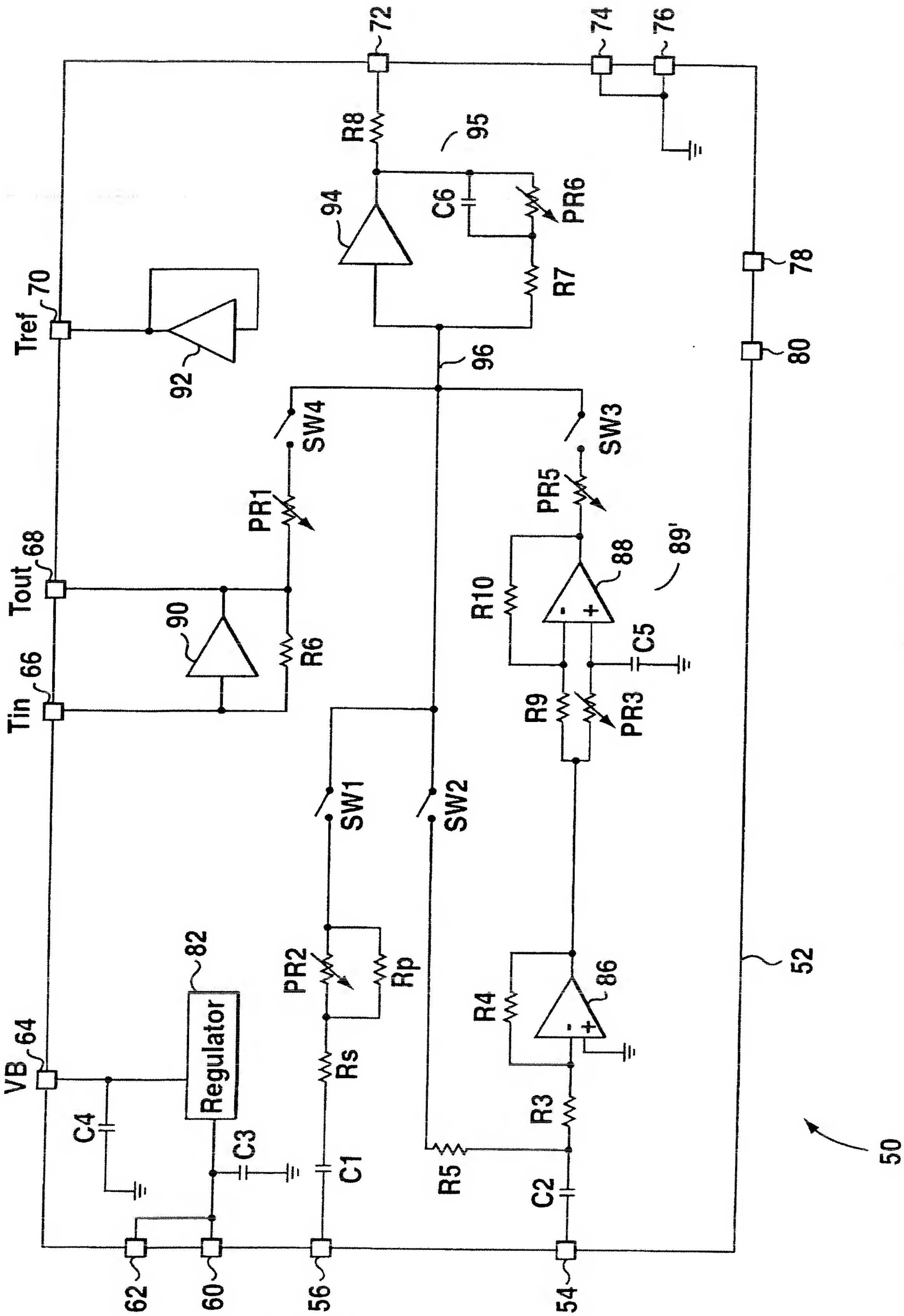

72
74
76
R8
95
94
C6
PR6
R7
Tref
70
92
96
SW4
SW3
PR1
PR5
Tout
68
89'
88
R10
90
R6
C5
Tin
66
R9
PR3
SW1
SW2
52
82
PR2
Rp
86
R4
VB
64
Regulator
Rs
R3
C4
C3
C1
R5
C2
50
62
60
56
54
78
80

FIG. 4

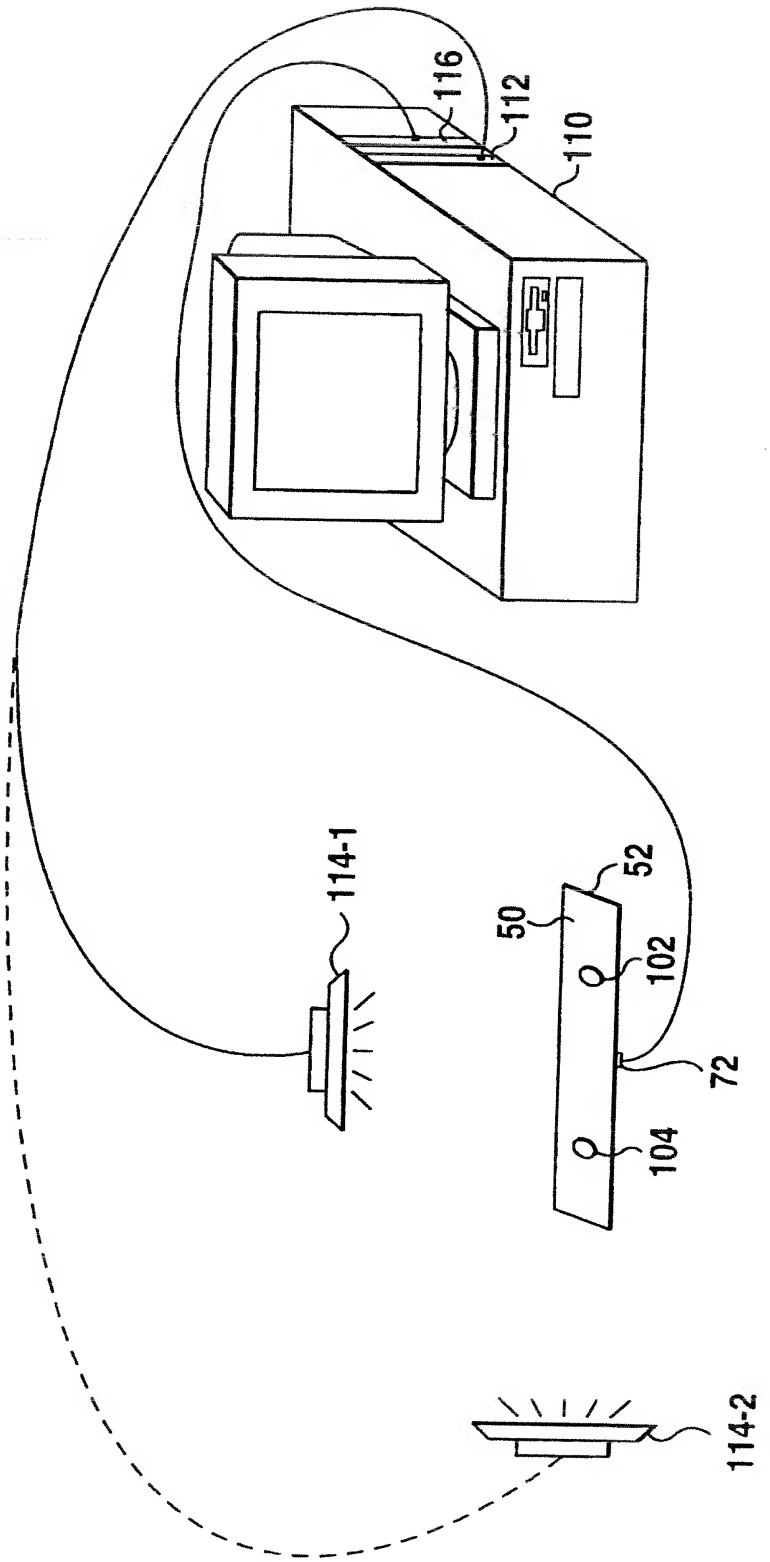


FIG. 5

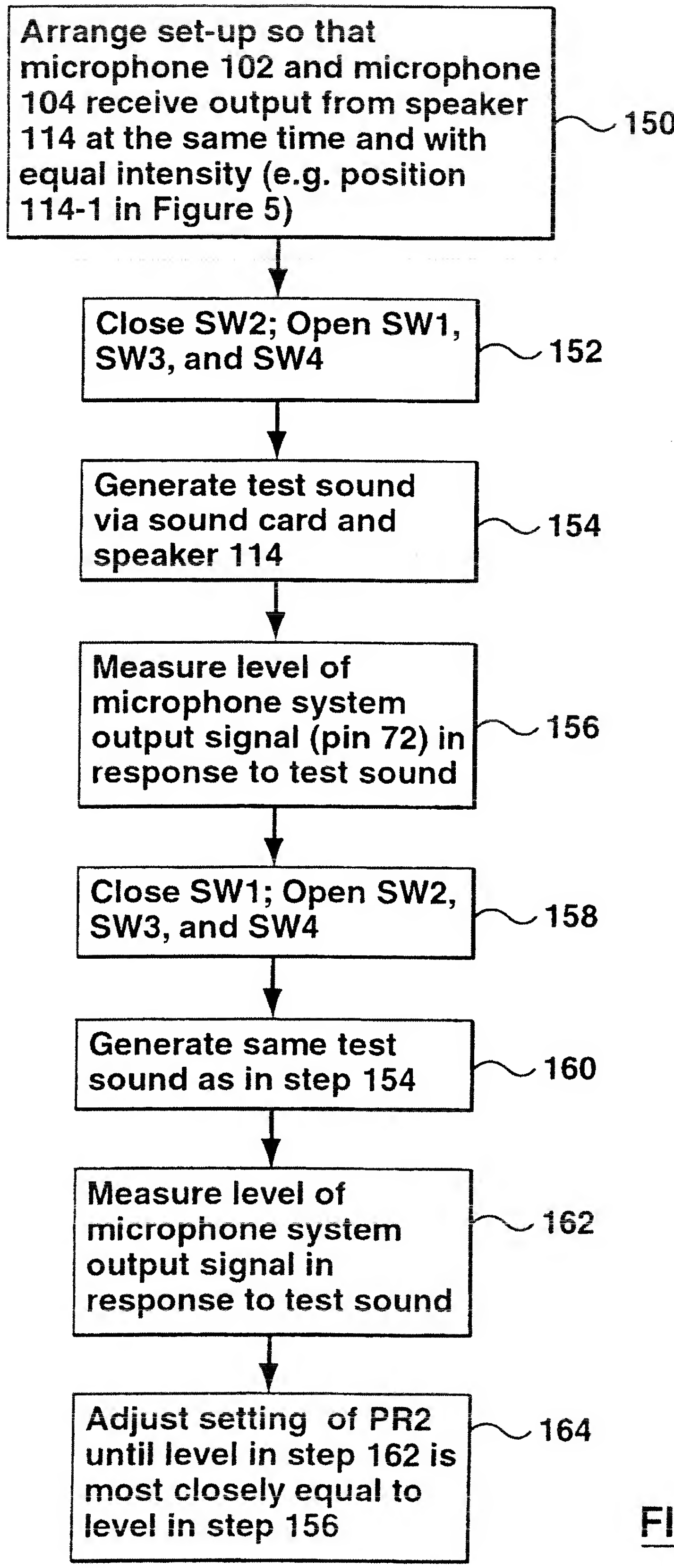

Arrange set-up so that microphone 102 and microphone 104 receive output from speaker 114 at the same time and with equal intensity (e.g. position 114-1 in Figure 5)
150
Close SW2; Open SW1, SW3, and SW4
152
Generate test sound via sound card and speaker 114
154
Measure level of microphone system output signal (pin 72) in response to test sound
156
Close SW1; Open SW2, SW3, and SW4
158
Generate same test sound as in step 154
160
Measure level of microphone system output signal in response to test sound
162
Adjust setting of PR2 until level in step 162 is most closely equal to level in step 156
164

FIG. 6

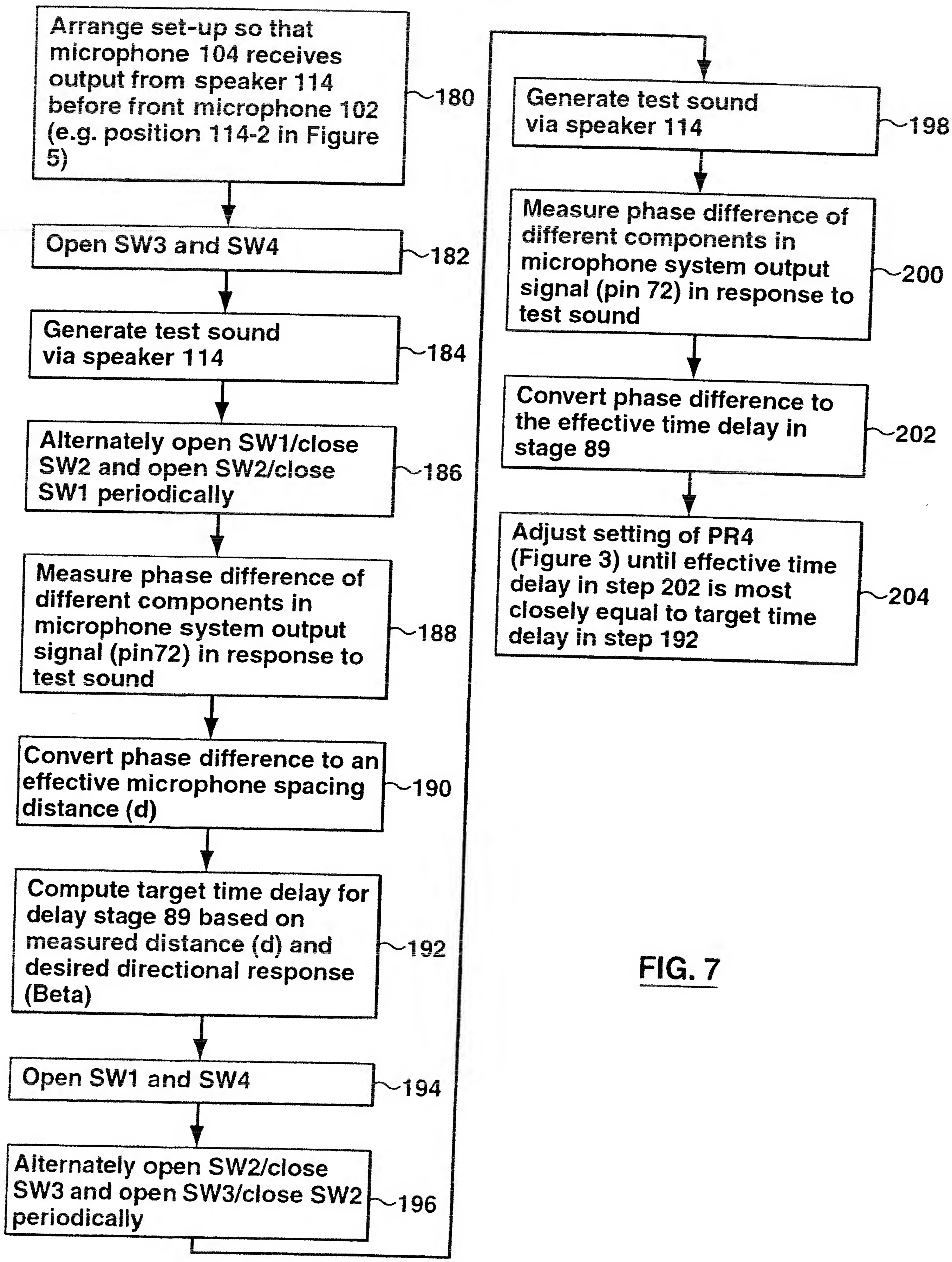

Arrange set-up so that microphone 104 receives output from speaker 114 before front microphone 102 (e.g. position 114-2 in Figure 5)
180
Open SW3 and SW4
182
Generate test sound via speaker 114
184
Alternately open SW1/close SW2 and open SW2/close SW1 periodically
186
Measure phase difference of different components in microphone system output signal (pin72) in response to test sound
188
Convert phase difference to an effective microphone spacing distance (d)
190
Compute target time delay for delay stage 89 based on measured distance (d) and desired directional response (Beta)
192
Open SW1 and SW4
194
Alternately open SW2/close SW3 and open SW3/close SW2 periodically
196
Generate test sound via speaker 114
198
Measure phase difference of different components in microphone system output signal (pin 72) in response to test sound
200
Convert phase difference to the effective time delay in stage 89
202
Adjust setting of PR4 (Figure 3) until effective time delay in step 202 is most closely equal to target time delay in step 192
204

FIG. 7

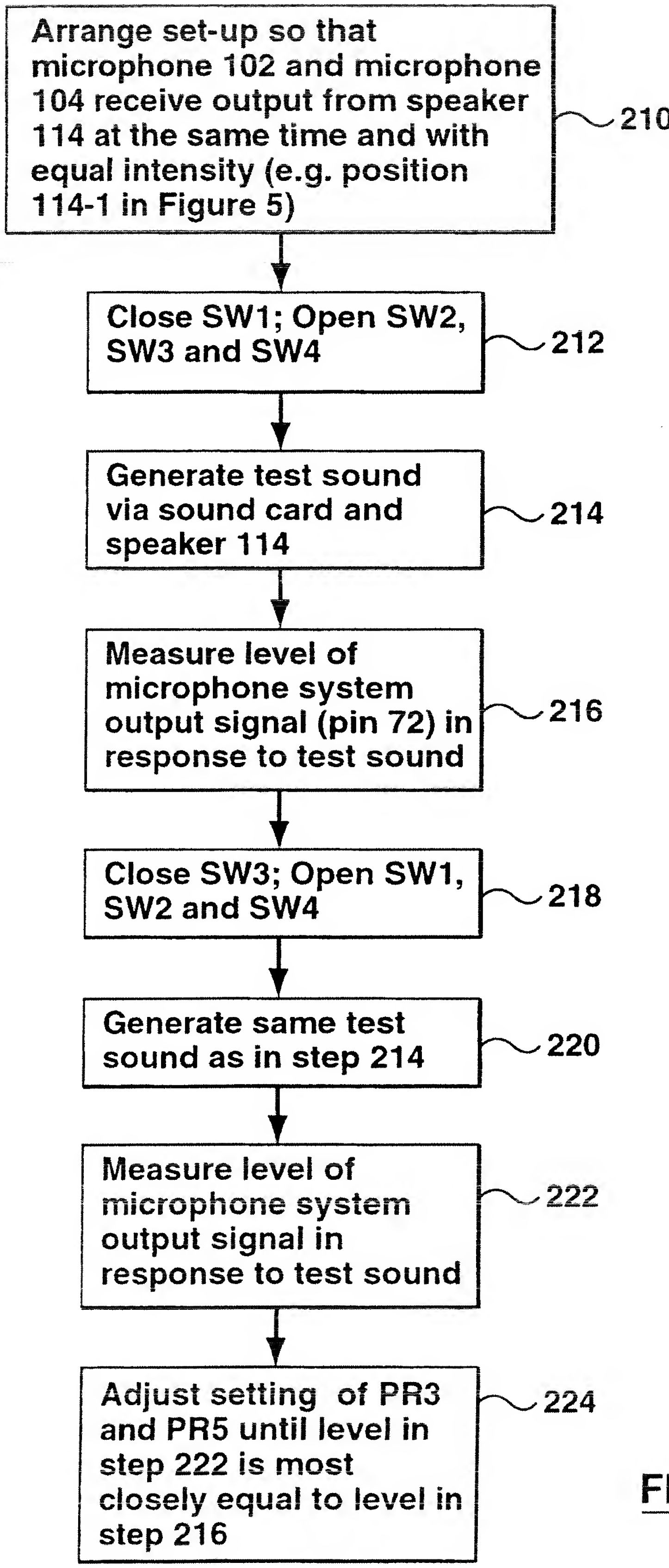

Arrange set-up so that microphone 102 and microphone 104 receive output from speaker 114 at the same time and with equal intensity (e.g. position 114-1 in Figure 5)
210
Close SW1; Open SW2, SW3 and SW4
212
Generate test sound via sound card and speaker 114
214
Measure level of microphone system output signal (pin 72) in response to test sound
216
Close SW3; Open SW1, SW2 and SW4
218
Generate same test sound as in step 214
220
Measure level of microphone system output signal in response to test sound
222
Adjust setting of PR3 and PR5 until level in step 222 is most closely equal to level in step 216
224

FIG. 8

INTERNATIONAL SEARCH REPORT

International Application No
PCT/CA 00/00463

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 H04R25/00 H04R1/40 H04R3/00

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 H04R

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	EP 0 499 699 A (PHONAK AG) 26 August 1992 (1992-08-26) the whole document	1-20
A	US 4 622 440 A (SLAVIN MARTIN J) 11 November 1986 (1986-11-11) column 2, line 54 -column 3, line 38; figure 1	1-20
A	US 4 399 327 A (YAMAMOTO MAKOTO ET AL) 16 August 1983 (1983-08-16) column 10, line 5 -column 14, line 9; figures 21-24	1-20

☐ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

° Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
14 August 2000	28/08/2000

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Nieuwenhuis, P

INTERNATIONAL SEARCH REPORT

Information on patent family members

Inter   onal Application No
PCT/CA 00/00463

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
EP 0499699 A	26-08-1992	CH 681411 A	15-03-1993
		AT 134814 T	15-03-1996
		DE 59107476 D	04-04-1996
		DK 499699 T	18-03-1996
		ES 2085405 T	01-06-1996
US 4622440 A	11-11-1986	AU 4104985 A	17-10-1985
		BE 902172 A	31-07-1985
		BR 8501694 A	10-12-1985
		DE 3512999 A	17-10-1985
		DK 161585 A	12-10-1985
		FR 2562789 A	18-10-1985
		GB 2158676 A	13-11-1985
		GR 850919 A	25-11-1985
		IT 1209948 B	30-08-1989
		JP 60244200 A	04-12-1985
		NL 8501042 A	01-11-1985
		NO 851432 A	14-10-1985
		PT 80273 A,B	01-05-1985
		SE 8501743 A	12-10-1985
		ZA 8502656 A	24-12-1985
US 4399327 A	16-08-1983	JP 1237615 C	31-10-1984
		JP 56104597 A	20-08-1981
		JP 59012239 B	21-03-1984
		JP 56116396 A	12-09-1981
		JP 62004039 B	28-01-1987
		DE 3102208 A	10-12-1981